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ABSTRACT (Maximum 200 words)

Significant progress was made in a number of aspects of stochastic and discrete event systems. A controlled switching diffusion model was developed to study systems with multiple modes or failure modes, such as aircraft with multiple operating modes, the hierarchical control of flexible manufacturing systems, and large scale interconnected power networks. In addition, a number of other optimal stochastic control problems with long time horizons were solved. An important problem in the adaptive control of a finite state Markov chain was solved, and significant progress was made along more general directions. New results on the risk-sensitive control of hidden Markov processes were obtained. Motivated by applications in hierarchical intelligent control, some important problems in the area of discrete event systems were solved.

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"STOCHASTIC ADAPTIVE ESTIMATION AND CONTROL"

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Abstract

Significant progress was made in a number of aspects of stochastic and discrete event systems. A controlled switching diffusion model was developed to study systems with multiple modes or failure modes, such as aircraft with multiple operating modes, the hierarchical control of flexible manufacturing systems, and large scale interconnected power networks. In addition, a number of other optimal stochastic control problems with long time horizons were solved. An important problem in the adaptive control of a finite state Markov chain was solved, and significant progress was made along more general directions. New results on the risk-sensitive control of hidden Markov processes were obtained. Motivated by applications in hierarchical intelligent control, some important problems in the area of discrete event systems were solved.

1. SUMMARY OF RESEARCH PROGRESS AND RESULTS

Realistic models of many engineering systems, including those in the fields of aerospace navigation and vehicular control, neural networks, the control of robotic manipulators, communication system design, and optimal control, involve unknown parameters, nonlinearities, and noise disturbances. The design of high performance control systems, in aerospace as well as other applications, generally requires the use of adaptive control techniques when the parameters are unknown or may be changing. With this motivation, we proposed research concerned with the study of several basic questions in the adaptive estimation and control of stochastic systems.

During the period supported by this grant, we have made significant progress both in areas we proposed to investigate and in related areas. In this section, we summarize the progress in those areas that have resulted in publications.

1.1 Stochastic Control

First, a controlled switching diffusion model was developed to study systems with multiple modes or failure modes, such as aircraft with multiple operating modes, the hierarchical control of flexible manufacturing systems, and large scale interconnected power networks [1], [14], [24]. On line implementable optimal feedback policies were derived for a discounted cost stochastic optimization problem in this setting. Our treatment of the optimization problem is based on a convex analytic approach which is interesting in its own right and is more flexible and powerful for certain other purposes, e.g. the pathwise average cost problem or problems with several constraints in which other approaches do not seem to be amenable. Using this method, we prove in [1], [14], [24] the existence of a homogeneous Markov nonrandomized optimal control law. Using the existence of such a control law, the existence of a unique solution in a certain class to the associated Hamilton-Jacobi-Bellman (HJB) equations is established and the optimal control law is characterized as a minimizing selector of an appropriated Hamiltonian. This methodology is used to solve a particular problem in the hierarchical control of flexible manufacturing systems; in this problem, the model involves a hybrid process in continuous time whose state is given by a pair $(X(t), S(t))$. Here, $X(t)$ denotes the downstream buffer stock of parts, which may have a negative value to indicate a backlogged demand. The continuous component $X(t)$ is governed by a controlled diffusion process with a drift vector which depends on the discrete component $S(t)$. Thus, $X(t)$ switches from one diffusion path to another as the discrete component $S(t)$ jumps form one state to another. On the other hand, the discrete component $S(t)$, denoting the number of operational machines, is influenced by the inventory size and production scheduling, and can also be controlled by various decisions such as produce, repair, replace, etc. Hence, $S(t)$ evolves as a "controlled Markov chain" with a transition matrix depending on the continuous component. The corresponding average cost optimization problem is considered in [12] and [19]. Under certain conditions, we establish the existence of stable Markov nonrandomized policy which is almost surely optimal for the pathwise long-run avereage cost criterion. We characterize the optimal policy as a minimizing selector of the Hamiltonian associated with the HJB equations. We apply these results to the

failure prone manufacturing system problem and show that the optimal production rate is of the hedging point type.

The optimal control of diffusions is considered in [2]. Under a penalizing condition on the cost or unstable behavior or under a Liapunov stability condition, we establish the existence of a stable Markov control law which is strong average optimal. We study in [3] average cost Markov decision processes on a countable state space, compact action space and with unbounded costs; we prove the existence of a stable stationary strategy which is optimal. In [11] and [20] we study Markov decision processes, with an infinite planning horizon, under a cost criterion obtained as a weighted combination of the discounted and long-run average cost criteria. In addition, a functional characterization is given for overtaking optimal policies, for problems with countable state spaces and compact control spaces.

We consider in [18], [23] Markov decision processes with an average cost criterion, general control and state spaces, and unbounded one-stage cost functions. We show how structural properties in the model can be used to obtain a functional characterization of optimal values and policies, in the form of an average cost optimality equation (ACOE). In particular, if the (discounted) value functions are convex, the ACOE is obtained as a limit of the corresponding discounted optimality equations. We further comment on the potential algorithmic impact of this and other structured solutions, and the application of the results to, e.g., inventory control problems.

In [21] we consider a risk-sensitive optimal control problem for hidden Markov models (HMM). Building upon recent results by Baras, James and Elliott, we investigate the structure of risk-sensitive controllers for HMM, via an examination of a popular benchmark problem. We obtain new results on the structure of the risk-sensitive controller by first proving concavity and piecewise linearity of the value function. Furthermore, we compare the structure of risk-sensitive and risk-neutral controllers.

In [4], an invited survey paper which appeared in a special issue of the *SIAM Journal on Control and Optimization* dedicated to Prof. Wendell Fleming, we present a comprehensive survey of the average cost control problem for discrete-time Markov processes. Our exposition covers from finite to Borel state and action spaces and includes a variety of methodologies to find and characterize optimal policies.

As a prelude to studying adaptive control, the problem of characterizing the effects that uncertainties and/or small changes in the parameters of a model can have on optimal policies is considered in [5]. It is shown that changes in the optimal policy are very difficult to detect, even for relatively simple models. By showing for a machine replacement problem modeled by a partially observed, finite state Markov decision process, that the infinite horizon, optimal discounted cost function is piecewise linear, we have derived formulas for the optimal cost and the optimal policy, thus providing a means for carrying out sensitivity analyses.

The stochastic adaptive control of finite state Markov chains with incomplete state observations and unknown parameters is investigated in [6], [7], [22]; in particular, we have studied certain classes of quality control, replacement, and repair problems. The general problem is solved, as well as a particular application in manufacturing; in addition, there are implications and possible applications in the study of neural networks, intelligent control, and the general issue of learning in stochastic adaptive control. In [6], we design a certainty equivalent adaptive controller and prove its optimality via an averaging method. In [7], we have investigated

the same problem, but by employing a different adaptive control law, known as Nonstationary Value Iteration (NVI). NVI, instead of computing the optimal policy for each value of the parameter and storing it (as with certainty equivalent policies), computes the control law on-line by performing one step of a dynamic programming algorithm at each time, using the most recent parameter estimate. Again, we show in [7] the optimality of this policy for this class of problems. A more general methodology for adaptive control of finite state Markov chains with incomplete state observations is presented in [15], [17].

1.2 Discrete Event Dynamical Systems

Motivated by applications in hierarchical intelligent control in which we envision an architecture with discrete event controllers at a high level interacting with continuous systems and controllers at lower levels, we have undertaken a significant program of research in Discrete Event Dynamical Systems (DEDS). We have studied the supervisor synthesis problem of DEDS through the use of synchronous composition of the plant and supervisor, thus simplifying the DEDS control methodology. Stability and stabilization of DEDS are studied in [8], [25]; these notions are presented in a more general setting than in previous work. Efficient tests for stability and stabilizability are derived. We address in [9] the supervisory synthesis problem for controlling the sequential (infinite string) behaviors of DEDS under complete as well as partial information through the use of synchronous composition. Closed form expressions for supremal languages are obtained, and supervisors are designed. In [10], [16] we take treat the state space of the DEDS, as opposed to the set of events, as the fundamental concept. We approach the problem of controlling (possibly infinite state) DEDS by using predicates and predicate transformers. The supervisory predicate control problem is introduced and solved. The problem of controlling DEDS under incomplete state observations is also considered and solved. Techniques for finding extremal solutions of boolean equations are used to derive minimally restrictive supervisors.

Many systems such as manufacturing systems, database management systems, communication networks, etc. can be modeled as input-output discrete event systems (I/O DEDS). In [13] we formulate and study the problem of stable realization of such systems. Given an input and an output language describing the sequences of events that occur at the input and the output, respectively, of an I/O DEDS, we study whether it is possible to realize the system as a unit consisting of a given set of buffers of finite capacity, called a dispatching unit. Effectively computable necessary and sufficient conditions for testing for stable and causal input-output maps are obtained.

Journal Publications

1. M. K. Ghosh, A. Arapostathis and S.I. Marcus, "An Optimal Control Problem Arising in Flexible Manufacturing Systems," *SIAM Journal on Control and Optimization,* **31**, September 1993, 1183-1204.

2. M.K. Ghosh and S.I. Marcus, "A Note on Controlled Diffusions with Long Finite Horizon," *Systems & Control Letters*, **16**, 1991, 379-385.

3. M.K. Ghosh and S.I. Marcus, "On Strong Average Optimality of Markov Decision Processes with Unbounded Costs," *Oper. Res. Letters*, **11**, 1992, 99-104.

4. A. Arapostathis, V. S. Borkar, E. Fernández-Gaucherand, M. K. Ghosh and S.I. Marcus, "Discrete-Time Controlled Markov Proceses with Average Cost Criterion: A Survey," *SIAM Journal on Control and Optimization,* **31**, March 1993, 282-344.

5. E. Sernik and S.I. Marcus, "Optimal Cost and Replacement Policy for a Markovian Replacement Problem," *J. Optimization Theory and Applications,* **71**, 1991, 105-126.

6. E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "Analysis of an Adaptive control Scheme for a Partially Observed Controlled Markov Chain," *IEEE Trans. Automatic Control*, June 1993, 987-993.

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8. R. Kumar, V. Garg and S.I. Marcus, "Language Stability and Stabilizability of Discrete Event Dynamical Systems," *SIAM Journal on Control and Optimization,* **31**, September 1993, 1294-1320.

9. R. Kumar, V. Garg and S.I. Marcus, "On Supervisory Control of Sequential Behaviors," *IEEE Transactions on Automatic Control,* **37**, December 1992, 1978-1985.

10. R. Kumar, V. Garg and S.I. Marcus, "Predicates and Predicate Transformers for Supervisory Control of Discrete Event Dynamical Systems," *IEEE Transactions on Automatic Control,* **38**, February 1993, 232-247.

11. E. Fernández-Gaucherand, M. K. Ghosh, and S.I. Marcus, "Controlled Markov Processes on the Infinite Planning Horizon: Weighted and Overtaking Cost Criteria," *Zeit. Oper. Res.,* **39**, 1994, 131-155.

12. M.K. Ghosh, A. Arapostathis and S.I. Marcus, "Ergodic Control of Switching Diffusions," submitted to *SIAM Journal on Control and Optimization.*

13. R. Kumar, V. Garg and S.I. Marcus, "Finite Buffer Realization of Input-Output Discrete Event Systems," submitted to *IEEE Trans. Automatic Control.*

Other Publications

14. M. K. Ghosh, A. Arapostathis and S. I. Marcus, "An Optimal Control Problem Arising in Flexible Manufacturing Systems," *Proc. 30th IEEE Conf. on Decision and Control*, Brighton, England, December 11-13, 1991, 1844-1849.

15. E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "A Methodology for the Adaptive Control of Markov Chains Under Partial State Information," *Proc. 1992 Princeton Conf. on Info. Sciences & Systems.*

16. R. Kumar, V. Garg and S. I. Marcus, "Using Predicate Transformers for Supervisory Control," *Proc. 30th IEEE Conf. on Decision and Control*, Brighton, England, December 11-13, 1991, 98-103.

17. E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "A Methodology for the Adaptive control of Markov Chains under Partial State Information," *Proc. 31st IEEE Conf. on Decision and Control,* December 16-18, 1992, Tucson, Arizona, 2750-2751.

18. E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "Convex Stochastic Control Problems," *Proc. 31st IEEE Conf. on Decision and Control,* December 16-18, 1992, Tucson, Arizona, 2179-2180.

19. M. Ghosh, A. Arapostathis, and S.I. Marcus, "Optimal Control of a Hybrid System with Pathwise Average Cost," *Proc. 31st IEEE Conf. on Decision and Control,* December 16-18, 1992, Tucson, Arizona, 1061-1066.

20. E. Fernández-Gaucherand, M. K. Ghosh, and S.I. Marcus, "Controlled Markov Processes on the Infinite Planning Horizon: Weighted and Overtaking Cost Criteria," *Proc. 32nd IEEE Conf. on Decision and Control,* December 15-17, 1993, San Antonio, Texas, 381-386.

21. E. Fernández-Gaucherand and S.I. Marcus, "Risk-Sensitive Optimal Control of Hidden Markov Models: A Case Study," to appear in *Proc. 32nd IEEE Conf. on Decision and Control,*, December, 1994, Orlando, Florida.

22. E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "Adaptive Control of a Partially Observed Controlled Markov Chain," in *Stochastic Theory and Adaptive Control,* T. E. Duncan and B. Pasik-Duncan, eds., Lecture Notes in Control and Information Sciences, Vol. 184, New York: Springer-Verlag, 1992, 161-171.

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3. RESEARCH PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT

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4. PAPERS PRESENTED

[i] M.K. Ghosh, A. Arapostathis and S.I. Marcus, "An Optimal Control Problem Arising in Flexible Manufacturing Systems," 30th IEEE Conf. on Decision and Control, December 11-13, 1991, Brighton, England.

[ii] R. Kumar, V. Garg and S. I. Marcus, "Using Predicate Transformers for Supervisory Control," 30th IEEE Conf. on Decision and Control, December 11-13, 1991, Brighton, England.

[iii] S.I. Marcus, "Introduction to Discrete Event Systems," University of Michigan, Ann Arbor, MI, January 23, 1992.

[iv] E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "A Methodology for the Adaptive Control of Markov Chains under Partial State Information," 26th Conference on Information Sciences and Systems, March 18-20, 1992, Princeton, NJ.

[v] S.I. Marcus, "Modeling and Control of Discrete Event Systems," Johns Hopkins University, Baltimore, MD, April 9, 1992.

[vi] S. I. Marcus, "Analysis and Control of Discrete Event Dynamical Systems" (Invited Plenary Lecture), Workshop on Discrete Event Systems, August 26-28, 1992, Prague, Czechoslovakia.

[vii] E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "Infinite Horizon Undiscounted Optimal Control of finite Stochastic Automata," SIAM Conference on Control and Its Applications, September 17-19, 1992, Minneapolis, Minnesota.

[viii] E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "Recent Results on Controlled Markov Processes with an Infinite Planning Horizon," SIAM Conference on Control and Its Applications, September 17-19, 1992, Minneapolis, Minnesota.

[ix] R. Kumar, V. Garg and S.I. Marcus, "Fixed Points and Their Applications to Supervisory Control of DES," SIAM Conference on Control and Its Applications, September 17-19, 1992, Minneapolis, Minnesota.

[x] M. Ghosh, A. Arapostathis, and S.I. Marcus, "Ergodic Control of Switching Diffusions Arising in the Modeling of a Flexible Manufacturing System," Workshop on Hierarchical Control for Real-time Scheduling of Manufacturing Systems, October 16-18, 1992, Lincoln, NH.

[xi] E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "Controlled Markov Processes with Average Criteria," ORSA/TIMS Joint National Meeting, November 2-4, 1992, San Francisco, CA.

[xii] E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "A Methodology for the Adaptive control of Markov Chains under Partial State Information," 31st IEEE Conf. on Decision and Control, December 16-18, 1992, Tucson, Arizona.

[xiii] E. Fernández-Gaucherand, A. Arapostathis, and S.I. Marcus, "Convex Stochastic Control Problems," 31st IEEE Conf. on Decision and Control, December 16-18, 1992, Tucson, Arizona.

[xiv] M. Ghosh, A. Arapostathis, and S.I. Marcus, "Optimal Control of a Hybrid System with Pathwise Average Cost," 31st IEEE Conf. on Decision and Control, December 16-18, 1992, Tucson, Arizona.

[xv] S. I. Marcus, "Recursive Adaptive Estimation and Control for Hidden Markov Models," CWI, June 5, 1993, Amsterdam, The Netherlands.

[xvi] E. Fernández-Gaucherand, M. K. Ghosh, and S.I. Marcus, "Controlled Markov Processes on the Infinite Planning Horizon: Weighted and Overtaking Cost Criteria," 32nd IEEE Conf. on Decision and Control, December 15-17, 1993, San Antonio, Texas.

[xv] S. I. Marcus, "Recursive Adaptive Estimation and Control for Hidden Markov Models," CWI, June 5, 1993, Amsterdam, The Netherlands.